

# Abstract

In the past two decades the core aircraft technology is going through a drastic change. The traditional technologies that is almost half a century old, is going through a complete revamp. In the new “More Electric Aircraft” technology many mechanical, pneumatic and hydraulic systems are being replaced by electrical and power electronic systems. Airbus-A380, Boeing B-787 are the pioneers in the family of these new breed of aircrafts. As the aircraft technology is moving towards “More Electric”, more and more electric motors and motor controllers are being used in new aircrafts. Number of electric motor drive systems has increased by about ten times in more electric aircrafts compared to traditional aircrafts. Weight of any electric component that goes into aircraft needs to be low to reduce the overall weight of aircraft so as to improve the fuel efficiency of the aircraft. Hence there is an increased need to reduce weight of motors and motor controllers in commercial aircraft.

High speed ironless axial flux permanent magnet brushless dc motors are becoming popular in the new more-electric aircrafts because of their ability to meet the demand of light weight, high power density, high efficiency and high reliability. However, these motors come with very low inductance, which poses a big challenge to the motor controllers in controlling the ripple current in motor windings. Multilevel inverters can solve this problem. Three-level inverters are proposed in this thesis for driving axial flux BLDC motors in aircraft. Majority of the motors in new more electric aircrafts are in the power range of 2kW to 20kW, while a few motor applications being in the range of 100kW to 150kW. Motor controllers in these applications run from 270Vdc or 540Vdc bus which is the standard in new more electric aircraft architecture.

Multilevel Inverter is popular in the industry for high power and high voltage applications, where high-voltage power switching devices like IGBT, GTO are popularly used. However multilevel inverters have not been tried in the low power range which is appropriate for aircraft applications. A detail analysis of practical feasibility of constructing three-level inverter in lower

power and voltage level is presented in this thesis. Analysis is presented that verify the advantages of driving low voltage and low power (300Vdc to 600Vdc and less than 100kW) motors with multilevel inverters. Practical considerations for design of MOSFET based three-level inverter are investigated and topological modifications are suggested. The effect of clamping diodes in the diode clamped multilevel inverters play an important role in determining its efficiency. SiC diodes are proposed to be used as clamping diodes. Further, it is realised that power loss introduced by reverse recovery of MOSFET body diode prohibits use of MOSFET in hard switched inverter legs. Hence, a technique of avoiding the reverse recovery losses of MOSFET body diode in three-level NPC inverter is conceived. The use of proposed multilevel inverter topology enables operation at high switching frequency without sacrificing efficiency. High switching frequency of operation reduces the output filter requirement, which in turn helps reducing size of the inverter. In this research work elaborate trade-off analysis is done to quantify the suitability of multilevel inverters in the low power applications.

For successful operation of three-level NPC inverter in aircraft electrical system, it is important for the DC bus structure in aircraft electric primary distribution system to be compatible to drive NPC inverters. Hence a detail study of AC to DC power conversion system as applied to commercial aircraft electrical system is done. Multi-pulse rectifiers using autotransformers are used in aircrafts. Investigation is done to improve these rectifiers for future aircrafts, such that they can support new technologies of future generation motor controllers. A new 24-pulse isolated transformer rectifier topology is proposed. From two 15° displaced 6-phase systems feeding two 12-pulse rectifiers that are series connected, a 24-pulse rectifier topology is obtained. Though, windings of each 12-pulse rectifiers are isolated from primary, the 6-phase generation is done without any isolation of the transformer windings. The new 24-pulse transformer topology has lower VA rating compared to standard 12-pulse rectifiers. Though the new 24-pulse transformer-rectifier solution is robust and simple, it adds to the weight of the overall system, as compared to the present architecture as the proposed topology uses isolated

transformer. Non-isolated autotransformer cannot provide split voltage at the dc-link that creates a stable mid-point voltage as required by the three-level NPC inverter. Hence, a new front-end AC-DC power conversion system with switched capacitor is conceived that can support motor controllers driven by three-level inverters. Laboratory experimental results are presented to validate the new proposed topology. In this proposed topology, the inverter dc-link voltage is double the input dc-link voltage.

An intense research work is performed to understand the operation of Trapezoidal Back EMF BLDC motor driven by three-Level NPC inverter. Operation of BLDC motor from three-Level inverter is primarily advantageous for low inductance motors, like ironless axial flux motors. For low inductance BLDC motor, very high switching frequency is required to limit the magnitude of ripple current in motor winding. Three-level inverters help limiting the magnitude of motor ripple current without increasing the switching frequency to very high value. Further, it is analysed that dc link mid-point current in three-level NPC inverter for driving trapezoidal BLDC motor has a zero average current with fundamental frequency same as switching frequency. Because of this, trapezoidal BLDC motors can easily be operated from three-level NPC inverter without any special attention given to mid-point voltage unbalance. One non-ideal condition arrives in practical implementation of the inverter that leads to non-zero average mid point current. Unequal gate drive dead time delays from one leg to other leg of inverter introduce dc-link mid-point voltage unbalance. For the motoring mode operation of trapezoidal BLDC motor drive, simple gate drive logic is researched that eliminates need of the gate drive dead-time, and hence solves the mid-point voltage unbalance issue. Simple closed loop control scheme for mid-point voltage balancing also is also proposed. This control scheme may be used in applications where very precise control of speed and torque ripple is warranted.

All the investigations reported in this thesis are simulated extensively on MATHCAD and MATLAB platform using SIMULINK toolbox. A laboratory experimental set-up of three-Level inverter driving axial flux BLDC motor is built. The three-level inverter, operating from 300Vdc

bus is built using 500V MOSFETs and 600V SiC diodes. All the control schemes are implemented digitally on digital signal processor TMS320F2812 DSP platform and GAL22V10B platforms. Experimental results are collected to validate the theoretical propositions made in the present research work.

At the end, in chapter 5, some future works are proposed. A new external voltage balance circuit is proposed where the inverter dc-link voltage is same as the input dc-link voltage. This topology is based on the resonant converter principle and uses a lighter resonant inductor than prior arts available in literature. Detail simulation and experimentation of this topology may be carried out to validate the industrial benefits of this circuit. It is also thought that current source inverters may work as an alternative to voltage source inverters for driving BLDC motors. Current source inverters eliminate use of bulky DC-link capacitors. Long term reliability of current source inverters is higher than voltage source inverters due to the absence of possibility of shoot-through. Further, in voltage source inverters, the voltage at the motor terminal is limited by the source voltage (dc-link voltage). This issue is eliminated in current source inverters. An interface circuit is conceived to reduce the size of dc-link inductors in current source inverters, pending detail analysis and experimental verification. The interface circuit bases its fundamentals on the principles of operation of multilevel inverters for BLDC motors that is presented in this thesis.